PULSE POWER FOR THE RAPIER "B AMPLIFIER" KrF LASER SYSTEM*

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Abstract

The RAPIER "B Amplifier" electron beam system has been completed and produces 36kJ of 450KeV electrons in a 150ns pulse to be used for pumping a KrF laser amplifier. The operating characteristics of the system have been studied. The efficiency of conversion of energy stored in the Marx generator to electron beam output is 72 ± 3% including an 89% designed transfer efficiency. The system is triggered electrically with a 150ns delay from the command trigger to machine output. The rms jitter for the six individual modules range from 1.6 to 3.9ns and the average timing difference between the earliest and latest module output is 12ns. Film dosimetry indicates no observable interaction between the magnetically isolated beams in the module diodes and fluorescence measurements do not indicate strong interaction in the gas filled laser cell. Current probe measurements show no significant change in beam size during the output pulse. Energy deposition profiles agree reasonably with Monte Carlo calculations up to pressures of 1.5 atm.

Introduction

The pulsed power system for the RAPIER 'B' amplifier KrF laser has been completed. It delivers 36kJ of 450KeV electrons in a 150ns pulse distributed over two 25x125 cm beam areas. The complete system consists of six pulsed power modules, a single laser cell, and several supporting subsystems. The pulsed power modules and laser cell are shown in Figure 1.

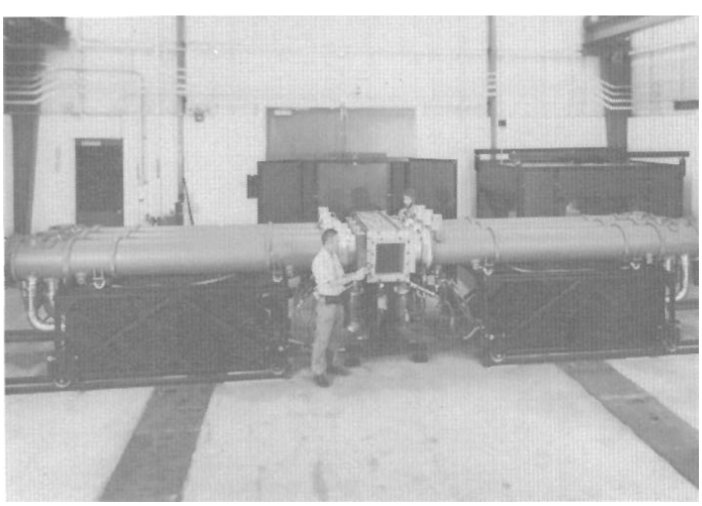

Fig. 1: RAPIER 'B' amplifier

Each consists of a Marx generator located in an oil filled tank beneath a 5Ω, coaxial, water dielectric Blumlein pulse forming line, an annular output switch, and a cold cathode electron beam diode. The design of these modules has been described previously.[1]

The individual components of the pulse power modules and assembly techniques were developed on a prototype module in a separate facility. Each of the six modules was assembled and tested individually in this facility prior to installation in the 'B' amplifier. Following installation, each group of three modules was tested separately to gain experience with the operation of multiple modules and to test supporting subsystems prior to the testing and characterization of the complete system.

Component Development

A prototype Marx generator was constructed and tested with a resistive load. Field grading, and triggering problems were considered solved upon completion of a series of 500 firings at 4/3 of the design voltage without any problems.

The output switch, PFL charging scheme, and Blumlein field grading techniques were tested extensively on a 60ns PFL at 1.15 times the design voltage prior to their incorporation into a full scale prototype of the entire pulsed power module. Some minor design problems, material problems and assembly procedures were considered resolved when a sequence of 200 shots were fired on a complete module including an electron beam diode at 1.15 times the design voltage without a single failure. The module was then fired an additional 250 times at its design voltage while electron beam measurements and diagnostic development were completed.

The six 'B' amplifier modules were assembled and subjected to an "acceptance" test. Each Marx generator was connected to a resistive load and a brief sequence of shots fired at successively higher voltages until 4/3 the designed operating voltage was attained. The Marx generator was then connected to the rest of the module and 25 shots were fired at the designed 450kV output voltage. Fifty shots were then fired at 15% above this voltage followed by an additional 10 shots at 450kV. During these tests the output voltage of the Marx generator, the voltage pulse that triggered the output switch, the pulse forming line output voltage and current, and the electron beam energy delivered to a carbon calorimeter located at the anode plane were monitored. The output switch trigger voltage monitor provided output switch timing data shown in Figure 2 for one of the modules. The standard deviation for nearly 100 shots fired over several weeks was 1.85ns.

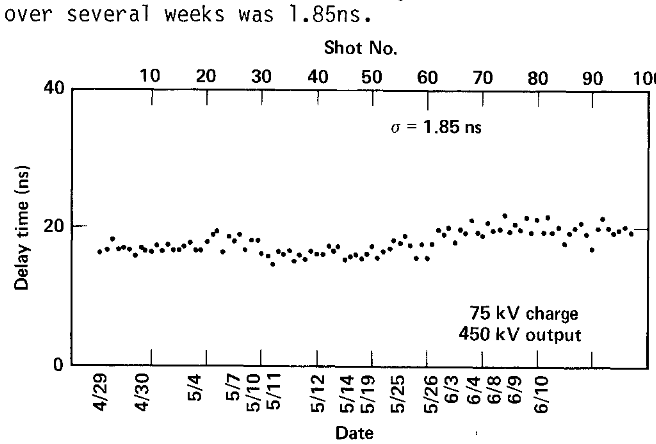

Fig. 2: Output switch jitter for single module

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14. ABSTRACT

The RAPIER "B Amplifier" electron beam system has been completed and produces 36kJ of 450KeV electrons in a l50ns pulse to be used for pumping a KrF laser amplifier. The operating characteristics of the system have been studied. The efficiency of conversion of energy stored in the Marx generator to electron beam output is 72 Â± 3% including an 89% designed transfer efficiency. The system is triggered electrically with a l50ns delay from the command trigger to machine output. The rms jitter for the six individual modules range from 1.6 to 3.9ns and the average timing difference between the earliest and latest module output is l2ns. Film dosimetry indicates no observable interaction between the magnetically isolated beams in the module diodes and fluorescence measurements do not indicate strong interaction in the gas filled laser cell. Current probe measurements show no significant change in beam size during the output pulse. Energy deposition profiles agree reasonably with Monte Carlo calculations up to pressures of 1.5 atm.

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Supporting Systems

A large number of supporting systems are necessary for the operation of the complete 'B' amplifier laser system. The two most noteworthy are the water system for the pulse forming lines and the diagnostic system.

The water system includes storage to permit draining of all of the lines and separate circuits for each line. A gravity return from each line to the storage reservoir permits the lines to be vented to the atmosphere preventing pressurization of the lines in the event of an output switch failure. Submersible pumps for each line allow all piping in the system to operate at positive pressure at flow rates of ∿ 2 gal/min. A separate circuit provides continuous filtering, deaeration, and deionization at ∿ 10 gal/min. Water is drawn from the storage reservoir into a vacuum chamber where the pressure is maintained below 50T by a liquid ring pump. The water is drawn from the chamber by a magnetically driven pump and circulated through 5μ filters and resin deionizing columns to keep the resistivity > 10MΩ-cm.

The principal concern in laser operation is with overall system performance, reproducibility, and fault detection, not detailed pulse shapes. In order to reduce the number of photographs necessary to determine performance, the 18 machine diagnostic signals were multiplied onto three dual beam oscilloscopes. Signals were delayed with analog delay lines and combined before connection to the input of the oscilloscopes where they were added to "staircase" waveforms to displace them vertically. The staircase waveforms were produced by digital circuits which also generated a series of pulses to retrigger the oscilloscope timebases. The result is shown in Figure 3. All six Marx generator output signals are displayed on one oscilloscope while the pulse forming line output voltages and currents are displayed on two other oscilloscopes. This technique sacrifices some signal fidelity in order to achieve compact displays.

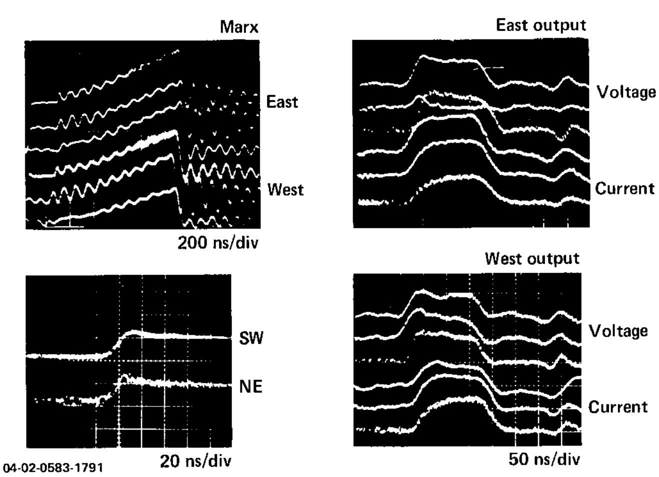

Fig. 3: Multiplexed diagnostics for six modules

Marx Generators

The six Marx generators were installed in two oil-filled tanks located under the pulse forming lines on opposite sides of the laser cell. One such assembly is shown in Figure 4.

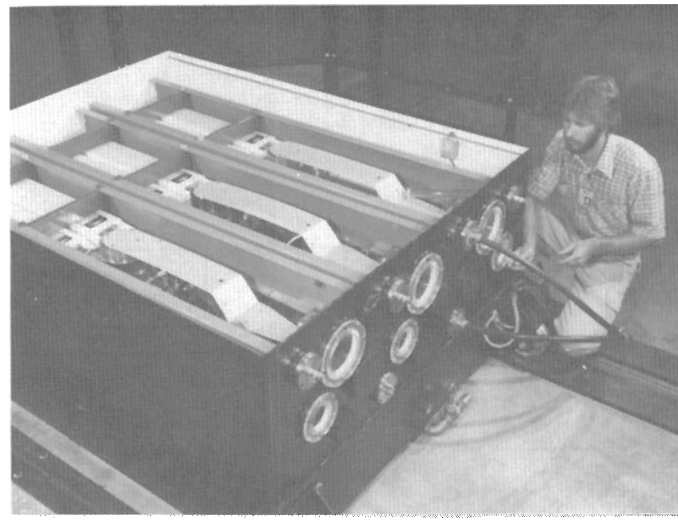

Fig. 4: Marx generators for east modules

The individual generators fit within the 42 cm repeat distance allocated to each module. The generators are charged from a common source through individual 30kΩ solution resistors which serve as fault isolation. The switch trigger electrodes are connected to a common input through 300Ω carbon resistor strings. This provides fault isolation between the generators but does provide coupling so that a prefire in one Marx will trigger the others and cause the three modules to fire normally even if early. The ability of one Marx firing to trigger the adjacent generators at as little as 70% of the set operating point was verified by reducing the switch pressure in one generator to induce a prefire while all were connected to resistive loads. The balanced PFL charging scheme employed in the 'B' amplifier requires connections to both terminals of each Marx generator. These connections are made through oil filled pipes which are barely visible in Figure 1.

Output Switches

The three output switches of adjacent modules are connected to a common spark gap whose firing generates the trigger pulse for the output switches. The trigger switch is located in the oil filled chamber behind the center module and the trigger pulse is distributed through oil filled pipes as shown in Figure 5.

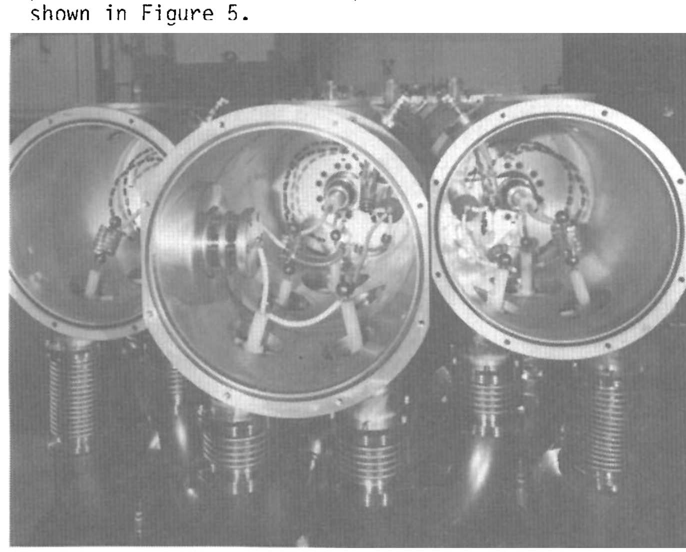

Fig. 5: Output switch trigger circuitry

Each output switch has its own mid-plane bias resistors, coupling capacitors, and trigger voltage monitor. The trigger switch has a mid-plane electrode which was initially connected to an RC circuit as shown in Figure 6.

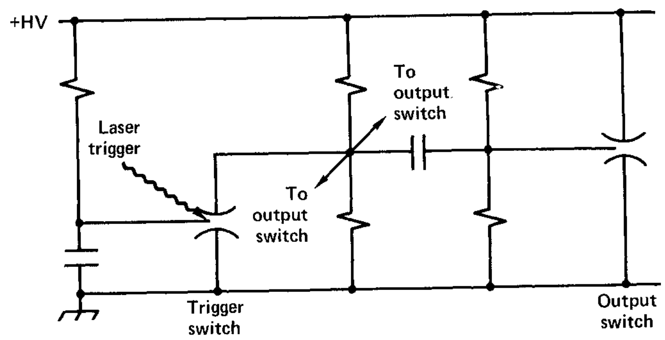

Fig. 6: Output switch trigger schematic

Initial plans called for laser triggering this switch with the mid-plane electrode providing fault protection. Since laser triggering was not required for pulsed power tests a simpler scheme was employed. The mid-plane capacitors of the two trigger switches were connected to a single over-volted spark gap located midway between the two ends of the machine (under the laser cell). The firing of this single gap triggered the two trigger switches which in turn triggered the output switches. The relative timing of the six modules was determined by displaying the PFL output voltage signals on separate oscilloscopes (bypassing the multiplexing system) together with a fiducial marker derived from the closure of the single common trigger gap. The relative times and rms jitters are listed in Table I averaged over a sequence of eleven shots. The difference in average firing times results principally from differences in the delay to breakdown for the output switches although transit time differences in the trigger distribution circuit ($\sim$ 4ns) do have an effect. The gas pressures in the output switches are equal since they are filled statically from a common source, but minor physical differences are inevitable and differences in charging waveforms are possible. The switch jitters are larger than measured for individual switches in part due to the inclusion of the two trigger switches in the measurement. The absolute time delay from the firing of the common gap to the arrival of the current pulse at the diode of the east center module was measured separately as 151 ± 2ns.

Module	σ	Δt	Δt	σ	Module
Nω	2.6	59.6	55.0	1.6	NE
ωC	2.0	55.0	54.9	2.0	EC
Sω	3.9	66.3	61.6	2.5	SE

Table I. Module Timing (in ns)

Electron Beams

Following the development of the prototype module, the principal remaining uncertainty in the operation of the complete pulsed power system involved the interaction of adjacent electron beams. The current delivered by the three modules on each side of the laser cell (270kA) is twice the critical current for beam self pinch in this geometry. In order to prevent the spatial collapse of the full beam, each module was provided with a separate cathode and a 3mm thick stainless steel plate between cathodes to allow current to flow between the anode and the pulse forming lines shown in Figure 7.

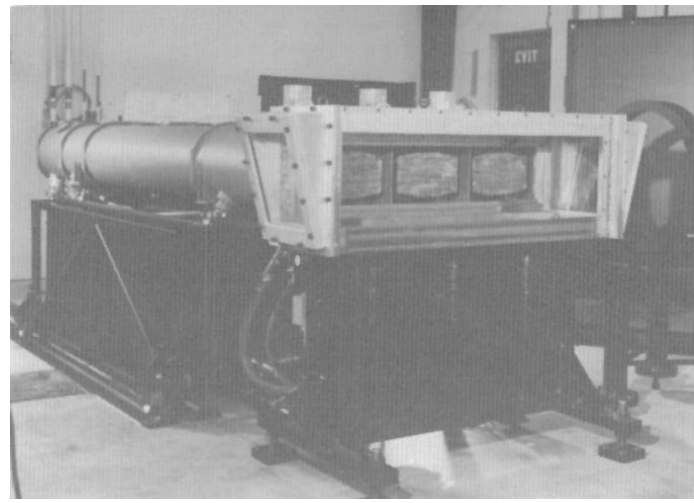

Fig. 7: Magnetically isolated diodes

These current paths effectively shielded the beam in each module from the magnetic fields produced in adjacent modules. Their effectiveness was verified by exposing a 25x125 cm^2 piece of lithographic paper to the entire electron beam produced by three modules. The resulting image showed no signs of beam collapse or indeed any interaction between the three beams.

The lithographic paper records only the time integrated beam profile. To determine if the beams were collapsing temporally the local current density was sampled with resistive collectors at several points including near the beam edge. The measurements showed little change in beam size during the pulse with some expansion of the beam during the first 50 ns near the beam edge.

The total energy delivered by the electron beam was measured with a carbon calorimeter located at the anode plane and covering the full 25x125 cm^2 beam area. The energy inferred from the temperature increase in the calorimeter was 19.1 ± 0.3kJ for the output of three modules. The stored energy in the Marx generator calculated from the charge voltage and measured capacitance leads to an overall conversion efficiency of 72 ± 2%. This efficiency includes an 11% loss due to the designed factor of two mismatch between the erected Marx capacitance and pulse forming line capacitance. Since the Marx charging power supply was designed to charge the system at constant current, the losses in the Marx charging resistors were small (< 2%). No attempt was made to measure or optimize the efficiency of the charging power supply.

The efficiency of beam transport through the cell foil support structure visible in Figure 8 was measured separately on the prototype module as 75-85% depending upon the choice of the "prefoil" installed on the cathode side of the support structure.

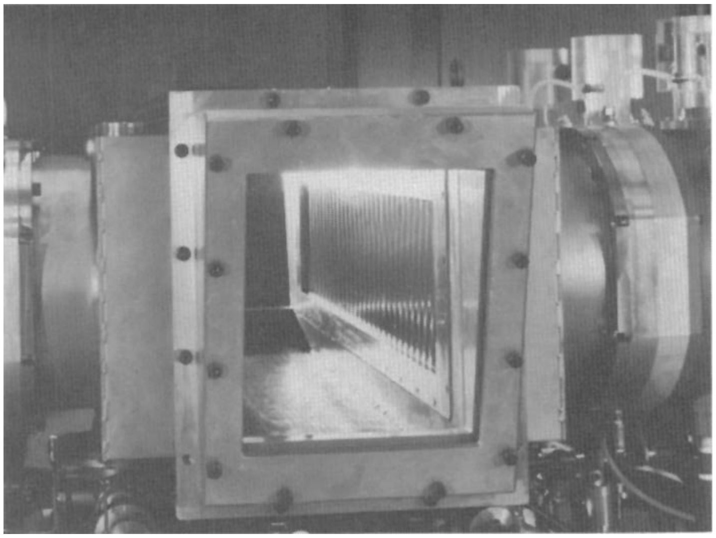

Fig. 8: Laser cell

The thinnest "prefoil" tested (0.25 mil aluminized Kapton) has proven serviceable. These measured efficiencies when combined with a Monte-Carlo calculation of energy deposited in the laser cell at 2 atm gas pressure yield a net efficiency of 36% for the ratio of energy deposited in an optically accessible region of the laser cell to the energy stored in the Marx generator.

Laser Cell

Since the self magnetic field of the beam injected into one side of the laser cell is capable of collapsing the beam in an axial distance of 1.5 cm, propagation into the 30 cm wide laser cell requires that sufficient current flow in the plasma formed by the interaction of the beam with the gas laser medium to nearly cancel the incident beam current. To determine if this cancellation was occurring the fluorescence of the auroral transition of atomic oxygen was photographed. The fluorescence was obtained by mixing 10T of O_2 with sufficient argon to fill the cell to the desired total pressure. Evidence of beam collapse was not observed and the fluorescence profiles agreed reasonably well with Monte-Carlo calculations of where the beam energy would be deposited in the absence of any interaction (see Figure 9).

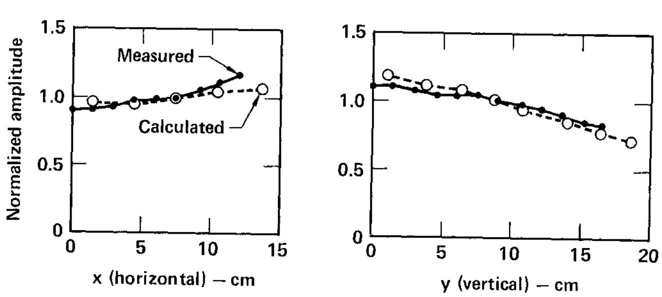

Fig. 9: Energy deposition profiles, Monte-Carlo calculations and measured fluorescence

In addition the total energy deposited in the gas as inferred from the pressure rise agreed with calculations up to total pressures of 1.5 atm. The inferred energy deposited was 11.5 ± 1kJ at 1.5 atm. However, at 2 atm there was a dramatic increase in the magnitude and uniformity of the photographed fluorescence accompanied by a decrease in Δp. Thus, the favorable results at lower pressures must be viewed cautiously.

Summary

The pulsed power system for the RAPIER 'B' amplifier KrF laser has been completed and the delivery of > 36kJ of electron beam energy in a 150ns pulse has been confirmed. The overall system efficiency has been measured as well as the timing between the six modules in the system. No deleterious interaction between the individual electron beams in the system has been observed.

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